California Environmental Protection Agency

Air Resources Board

# Detailed California-Modified GREET Pathway for Cellulosic Ethanol from Forest Waste

**This is a preliminary estimate of the carbon intensity for the fuel derived from the feedstock presented in this document. At this time, this document has been provided for informational purposes only. Staff is in the process of obtaining additional information to refine and/or modify the values presented in this document. The refinement is both for direct and indirect effects. When staff has completed the analysis, a final value will be presented in the future for the fuel presented in this document.**

**Stationary Source Division**

**Release Date: February 27, 2009**

**Version 2.1**

*The Staff of the Air Resources Board developed this preliminary draft version as part of the Low Carbon Fuel Standard Regulatory Process*

The ARB acknowledges contributions from the California Energy Commission, TIAX, and Life Cycle Associates during the development of this document

When reviewing this document, please submit comments directly to:

Anil Prabhu: aprabhu@arb.ca.gov
Chan Pham: cpham@arb.ca.gov
Alan Glabe : aglabe@arb.ca.gov
Jim Duffy : jduffy@arb.ca.gov

These comments will be compiled, reviewed, and posted to the LCFS website in a timely manner.

# TABLE OF CONTENTS

# LIST OF FIGURES



# LIST OF TABLES

# SUMMARY

## CA-GREET Model Pathway for Denatured Forest Waste Ethanol

A Well-To-Tank (WTT) Life Cycle Analysis of a fuel (or blending component of fuel) pathway includes all steps from feedstock production to final finished product. Tank-To-Wheel (TTW) analysis includes actual combustion of fuel in a motor vehicle for motive power. Together WTT and TTW analysis are combined together to provide a total Well-To-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET)[1] developed by Argonne National Laboratory has been used to calculate the energy use and Greenhouse gas (GHG) emissions during the entire process from forest waste collection, forest waste processing to ethanol and transportation to a blending station. The model however, was modified by TIAX under contract to the California Energy Commission during the AB 1007 process[2]. Changes were restricted to mostly input factors (electricity generation factors, crude transportation distances, etc.) with no changes in methodology inherent in the original GREET model. This model formed the basis for several fuel pathway documents published on the LCFS website in mid-2008. Subsequent to this, the Argonne Model was updated in September 2008. To reflect the update and to incorporate other changes, staff contracted with Life Cycle Associates to update the CA-GREET model. This updated California modified GREET model (v1.8b)[3] (released February 2009) forms the basis of this document. It has been used to calculate the energy use and greenhouse gas (GHG) emissions associated with a WTW analysis of the cellulosic ethanol from forest waste.

This document details the energy and inputs required to produce ethanol from forest waste outside of California and transporting the ethanol by rail to blending terminals in California for blending with CARBOB. Forest waste typically refer to those parts of trees unsuitable for sawlogs such as treetops, branches, small-diameter wood, stumps, leaves, dead wood and even poorly-formed whole trees, as well as undergrowth and low-value species. Nearly 20 billion cubic feet of wood is removed on an annual basis from lands in the United States. Of that volume, 16 percent is classified as logging waste, according to U.S. Department of Agriculture (USDA). This material is mainly tree tops and small branches that have been considered uneconomical to harvest. The USDA Forest Service Inventory and Analysis[4] program estimates that in 2001, 61 million dry tons of residuals are available annually from harvesting and fuel reduction activities. A recovery system, which would follow behind a conventional logging operation, could recover 60 percent or 40 million dry tons of this waste for potential bioenergy and bio-based product markets[5].

Well-to-tank greenhouse gas emissions are also calculated based on the energy results and provided in this document. The WTT components include forest waste collection and transport to ethanol plant, ethanol production and ethanol transportation and distribution (T&D). TTW is not included here since ethanol is typically not used directly as a fuel in an automobile. It is blended with CARBOB for use as California

Reformulated Gasoline (CaRFG). Also, ethanol is denatured before being transported from a production plant. This document though presents results only on an anhydrous ethanol (distilled ethanol >99.6% purity) basis. The details of blending anhydrous ethanol with a denaturant and its subsequent use in CaRFG are provided in the CaRFG document which is available on the LCFS website.

Several general descriptions and clarification of terminology used throughout this document are:

- CA-GREET employs a recursive methodology to calculate energy consumption and emissions. To calculate WTT energy and emissions, the values being calculated are often utilized in the calculation. For example, crude oil is used as a process fuel to recover crude oil. The total crude oil recovery energy consumption includes the direct crude oil consumption and the energy associated with crude recovery (which is the value being calculated).

- Btu/mmBtu is the energy input necessary in Btu to produce one million Btu of a finished (or intermediate) product. This description is used consistently in CA-GREET for all energy calculations.

- $gCO_2e$/MJ provides the total greenhouse gas emissions on a $CO_2$ equivalent basis per unit of energy (MJ) for a given fuel. Methane ($CH_4$) and nitrous oxide ($N_2O$) are converted to a $CO_2$ equivalent basis using IPCC (Intergovernmental Panel on Climate Change) global warming potential values and included in the total.

- CA-GREET assumes that VOC and CO are converted to $CO_2$ in the atmosphere and includes these pollutants in the total $CO_2$ value using ratios of the appropriate molecular weights.

- Process Efficiency for any step in CA-GREET is defined as:

  Efficiency = energy output / (energy output + energy consumed)

- Note that rounding of values has not been performed in several tables in this document. This is to allow stakeholders executing runs with the CA-GREET model to compare actual output values from the CA-modified model with values in this document.

Figure 1 below outlines the discrete components that comprise the forest waste ethanol pathway, from waste collection to ethanol transport and distribution.

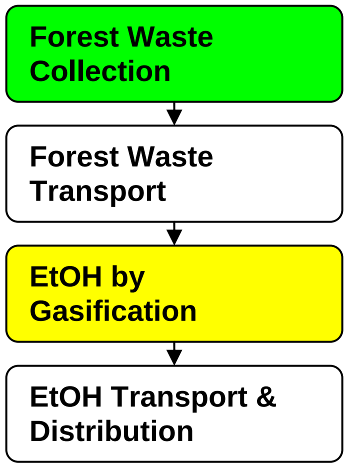



*Figure 1. WTT Components for Anhydrous Ethanol from Forest Waste*

Table A below summarizes the fuel cycle energy inputs by stage (Btu/mmBtu) and Table B summarizes the major GHG emission categories and intensities ($gCO_2e/MJ$). The Tables present energy and emission results relative to the energy content (LHV) of anhydrous ethanol. Note that due to negative entries from co-product credits, all %s have not been reported in Tables A and B. Complete details of all energy inputs and GHG emissions are provided in Appendix A. A list of all inputs is provided in Appendix B.

*Table A. Energy Use Summary for Forest Waste Ethanol*

| Forest Waste Ethanol WTT Energy Components | Energy (Btu/mmBtu) | % Energy Contribution |
|---|---|---|
| Forest Waste Collection | 110,817 | 5.12% |
| Forest Waste Transportation | 47,773 | 2.21% |
| Ethanol Production by gasification | 970,889 | 44.88% |
| Ethanol T&D | 34,010 | 1.6% |
| **Total Well-To-Tank** | **1,163,490** | **53.78%** |
| **Total Tank-to-Wheel** | **1,000,000** | **46.22%** |
| **Total Well-to-Wheel** | **2,163,490** | **100%** |

*Table B. GHG Emissions Summary for Forest Waste Ethanol*

| Forest Waste Ethanol WTT GHG Components | GHGs (g/MJ) | % Emission Contribution |
|---|---|---|
| Forest Waste Collection | 8.61 | |
| Forest Waste Transportation | 3.67 | |
| Ethanol Production | 136.60 | |
| $CO_2$ Credit from Waste Burning | (-130.15) | |
| Ethanol T&D | 2.67 | |
| **Total Well-To-Tank** | **21.40** | **100%** |
| **Total Tank-to-Wheel** | **0.0** | **0.0%** |
| **Total Well-to-Wheel** | **21.40*** | **100%** |

***** Note: Ethanol is not used directly as a fuel in CA but blended with CARBOB to produce CaRFG. Use of CaRFG in a light-duty vehicle generates $CO_2$ and other tailpipe emission species. When these are added (appropriately weighted) to the value in the table above, the WTW GHG emissions is calculated to be **22.20 g$CO_2$e/MJ** for cellulosic ethanol from forest waste as detailed in this document. Details of this calculation are provided in the CaRFG document.

**WTT Details**

This section provides a breakdown of the various energy and related GHG emissions for all the various components of the ethanol pathway detailed in Figure 1. Complete details including calculations, equations, etc. are provided in Appendix A.

FOREST WASTE COLLECTION

Table C provides a breakdown of energy input from each fuel type used for collection of forest waste. Table D provides information on GHG emissions related to the use of energy for collection of forest waste. Additional details are provided in Appendix A.

*Table C. Total Energy Input for Collection of Forest Waste*

| Fuel Type | Total Energy (Btu/dry ton) |
|---|---|
| Diesel fuel | 671,964 |
| Electricity | 92,445 |
| Total Energy for Forest waste Farming (Btu/dry ton) | 764,409 |
| **Total Energy for Trees Farming (Btu/mmBtu)** | **110,817** |

See Table 1.02

*Table D. GHG Emissions from Collection of Forest Waste*

| Emission Species | GHG ($gCO_2e$/mmBtu) |
|---|---|
| VOC | 35.48 |
| CO | 67.87 |
| $CH_4$ | 260 |
| $N_2O$ | 29.8 |
| $CO_2$ | 8,692 |
| Total GHG ($gCO_2e$/mmBtu) | 9,085 |
| **Total GHG ($gCO_2e$/MJ)** | **8.6** |

See Table 1.07

FOREST WASTE TRANSPORT

Table E details the energy inputs required to transport forest waste from the forest to the ethanol production plant. Table F provides details of the associated GHG emissions related to transportation of forest waste from the forest to the ethanol plant.

*Table E. Forest Waste Transport Energy*

| **Transport Mode** | **Energy Consumption (Btu/dry ton)** |
|---|---|
| Forest to Ethanol Plant by Heavy Duty Truck | 329,536 |
| **Total (ethanol) (Btu/mmBtu)** | **47,773** |

See Table 2.02

*Table F. Forest Waste Transport – Total GHG Emissions*

| **Transport Mode** | **$CH_4$ ($gCO_2e$/ mmBtu)** | **$N_2O$ ($gCO_2e$/ mmBtu)** | **VOC and CO Conversion ($gCO_2e$/mm Btu)** | **$CO_2$ (g/mmBtu)** | **GHG ($gCO_2e$/ mmBtu)** | **GHG ($gCO_2e$/MJ)** |
|---|---|---|---|---|---|---|
| Forest to Ethanol Plant - Heavy Duty Truck | 102.25 | 26.8 | VOC: 4.8<br>CO: 10.7 | 3,743 | 3,888 | **3.67** |

See Table 2.06

ETHANOL PRODUCTION

Table G details the energy inputs required to produce ethanol from forest waste. Table H provides details of the associated GHG emissions related to production of ethanol. Table I provides details of $CO_2$ credit generated by burning part of forest waste to generate process energy.

*Table G. Ethanol Production Energy Use*

| Fuel Type | Total Energy (Btu/dry ton) |
|---|---|
| Diesel | 392 |
| Forest Waste used as Fuel | 70,217 |
| Natural Gas | 3,461 |
| Total energy input for ethanol production (Btu/gal) | 74,071 |
| **Total energy input (Converted to Btu/mmBtu)** | **970,889** |

See Table 3.02

*Table H. GHG Emissions for Ethanol Production*

| GHG Species | GHG Emissions g/mmBtu |
|---|---|
| VOC | 6.2 |
| CO | 82.5 |
| $CH_4$ | 10.0 |
| $N_2O$ | 11.70 |
| $CO_2$ | 140,248 |
| Total GHGs ($gCO_2e$/mmBtu Anhydrous) | 144,101 |
| **Total GHGs ($gCO_2e$/MJ)** | **136.60** |

See Table 3.05

*Table I. GHG Emission Credits from Burning Forest Waste as Fuel*

| **Emissions** | |
|---|---|
| $CO_2$ (g/gal) | -10,476 |
| $CO_2$ ($gCO_2e$/mmBtu) | -137,312 |
| **GHG ($gCO_2e$/MJ)** | **-130.15** |

See Table 3.06

## ETHANOL TRANSPORT AND DISTRIBUTION

Transport from the ethanol plant to the bulk terminal or storage facility is accomplished primarily by rail (with short truck delivery to terminal or storage facility). The local distribution step involves transporting ethanol to a gasoline blending terminal where it is blended with gasoline to produce RFG. Ethanol is transported by truck to the blending terminal. Table J details the energy inputs required to transport ethanol. Table K provides details of the associated GHG emissions related to ethanol transport and distribution.

*Table J. Energy Use for Ethanol Transport and Distribution (T&D)*

| Transport Mode | Btu/mmBtu |
|---|---|
| Heavy Duty Truck Transport | 2,885 |
| Rail Transport | 25,973 |
| **Total Transport** | **28,858** |
| **Total Distribution (Btu/mmBtu)** | **5,152** |
| **Total T&D (Btu/mmBtu)** | **34,010** |

See Table 4.02

*Table K. GHG Emissions Related to Ethanol Transport and Distribution*

| Transport Mode | $CO_2$e (g/mmBtu) |
|---|---|
| Transported by Rail | 2,102 |
| Transported by Heavy Duty Truck | 234 |
| Distributed by Heavy Duty Truck | 418 |
| Total | 2,815 |
| **Total (g$CO_2$e/MJ)** | **2.67** |

See Table 4.04

**TTW Details**

COMBUSTION EMISSIONS FROM ETHANOL

Ethanol is assumed to be not used directly as a fuel in California. It is mixed with a gasoline blending component to produce California Reformulated Gasoline (CaRFG). Ethanol is also not transported without blending with a denaturant such as gasoline. For this document, there are no TTW contributions since the $CO_2$ released from combustion is considered neutral since the $CO_2$ was fixed from the atmosphere during the growth of the cellulosic feedstock (forest waste here). For details on CaRFG where denatured ethanol is used as a blend, refer to the CaRFG document available from the LCFS website.

(This page intentionally left blank.)

# APPENDIX A

(This page intentionally left blank.)

# SECTION 1. FOREST WASTE COLLECTION

## 1.1 Energy Use for Collection of Forest Waste

This section presents the direct energy inputs for collection of forest waste. To recover tree tops, thinning for wildfire reduction, and other forest management practices, the CA-GREET model calculates energy and emissions based on the quantity of fuel (Btu) per quantity of product (dry ton of forest waste), rather than using energy efficiencies, as the petroleum pathways do in CA-GREET. The total input energy per dry ton of forest waste collection is **612,700** (CA-GREET default) with the mix of fuel types shown in Table 1.01.

*Table 1.01. Direct Energy Inputs by Fuel/Energy Input Type for Collection of Forest Waste*

| **Fuel Type** | **Fuel Share** | **Formula** | **Primary Energy Input (Btu/dry ton)** |
|---|---|---|---|
| Diesel fuel | 94.3% | 94.3%*612,700 | 577,776 |
| Electricity | 5.7% | 5.7%*612,700 | 34,924 |
| **Direct Energy Consumption for Forest Waste Collection (Btu/dry ton)** | | | **612,700** |

The energy inputs are direct inputs and not total energy required. CA-GREET accounts for the 'upstream' energy associated with fuels by multiplying with appropriate factors which are shown in Table 1.02. Values used to calculate total energy in Table 1.02 are shown in Table 1.03.

*Table 1.02. Calculating Total Energy Input by Fuel for Collection of Forest Waste*

| **Fuel Type** | **Formula** | **Total Energy (Btu/dry ton)** |
|---|---|---|
| Diesel fuel | $A*[1+((B*C)+D)/10^6]$ | 671,964 |
| Electricity | $E*(F+G)/10^6$ | 92,445 |
| Total Energy for Forest Waste Collection (Btu/dry ton) | | 764,409 |
| **Total Energy for Forest Waste Collection (Btu/mmBtu)** | | **110,817** |

Note: The energy use for anhydrous ethanol is calculated from:
(Energy waste collection (Btu/dry ton) / (Ethanol Yield (gal/dry ton) * LHV of Anhydrous Ethanol (Btu/gal)))*$10^6$

where LHV of anhydrous ethanol is 76,330 Btu/gal.
Ethanol yield from forest waste is 90.4 gal/dry ton as CA-GREET default

(764,409 (Btu/dry ton) / (90.4 (gal/dry ton)*76,330 (Btu/gal))) x $10^6$ = 110,817 Btu/mmBtu

*Table 1.03. Values Used in Table 1.02*

| Factor | Description | Value | Reference |
|---|---|---|---|
| A | Direct Diesel input | 577,776 Btu/dry ton | calculated in Table 1.01 |
| B | Crude energy | 39,212 Btu/mmBtu | CA-GREET calculated – Cell B183 *Petroleum* tab |
| C | Diesel loss factor | 1.0 | CA-GREET default value |
| D | Conventional Diesel energy | 123,805Btu/mmBtu | CA-GREET calculated - Cell K183 *Petroleum* tab |
| E | Direct electricity input | 34,924 Btu/dry ton | calculated in Table 1.01 |
| F | Stationary electricity feedstock production | 85,708 Btu/mmBtu | CA-GREET calculated - Cell B84 *Electric* tab |
| G | Stationary electricity fuel consumption | 2,561,534 Btu/mmBtu | CA-GREET calculated - Cell C84 *Electric* tab |

The factors listed in Table 1.03 are derived from the energy contributions of all other fuels that were used to produce ethanol. The derivation of the WTT energy inputs are described in the pathway documents for diesel and for electricity. In the case of forest waste, the default average U.S. parameters were applied for diesel production and power generation.

**1.2 GHG Emissions from Collection of Forest Waste**

CA-GREET calculates carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) emissions for each component of the pathway and uses IPCC Global Warming Potentials (GWPs)[6] to calculate $CO_2$ equivalent values for methane and nitrous oxide (see Table 1.04). For VOC and CO, CA-GREET uses a carbon ratio to calculate $CO_2$ equivalent values which are detailed in a note below Table 1.04. These are based on the oxidation of CO and VOC to $CO_2$ in the atmosphere.

*Table 1.04. Global Warming Potentials for Gases*

| GHG Species | GWP (relative to $CO_2$) |
|---|---|
| $CO_2$ | 1 |
| $CH_4$ | 25 |
| $N_2O$ | 298 |

Note: values from mmBtu to MJ have been calculated using 1 mmBtu = (1/1055) MJ
Carbon ratio of VOC = 0.85 grams so $CO_2$/MJ = grams VOC*(0.85)*(44/12) = 3.1
Carbon ratio of CO = 0.43 grams so $CO_2$/MJ = grams CO/mmBtu*(0.43)*(44/12) = 1.6
where 44 and 12 are molecular weights of $CO_2$ and C, respectively.

The greenhouse gas emissions are determined separately for $CO_2$, $CH_4$ and $N_2O$ in CA-GREET using the direct energy inputs presented in Section 1.1 (Btu/dry ton) and the combustion and upstream emissions for the energy input. CA-GREET calculates the emissions for each fossil fuel input by multiplying fuel input (Btu/dry ton) by the total emissions from combustion, crude production and fuel production. The electricity emissions are calculated by multiplying the electricity input (Btu/dry ton) by the total (feedstock plus fuel) emissions associated with the chosen electricity mix (from the *Electricity* Tab in CA-GREET model). Table 1.05 below shows equations and calculated values by fuel type for $CO_2$ emissions. Equations and values for $CH_4$ and $N_2O$ are not shown, but use the same formula structure. Table 1.06 provides values for parameters used in the equations in Table 1.05.

*Table 1.05. CA-GREET Calculations for $CO_2$ Emissions from Forest Waste (from Upstream Sources)*

| Fuel | Formula | $CO_2$ Emissions (g/dry ton) |
|---|---|---|
| Diesel | $[(A)*[(B)*(C) + (D)*(E)+(F)*(G)+(H)*(I)+(J)*(K)+(L)]]/10^6$ | 52,266 |
| Electricity | $[(M)*[(N)+(O)]]/10^6$ | 7,693 |
| **Total $CO_2$ emissions (g/ton)** | | **59,960** |
| **Conversion to total $CO_2$ emissions (g/mmBtu)** | | **8,692** |

Note: The calculations for $CH_4$ and $N_2O$ are analogous. Relevant parameters here are calculated values in CA-GREET, except for technology shares, which are direct inputs.

*Table 1.06. CA-GREET Calculations for $CO_2$ Emissions Associated with Collection of Forest Waste*

| Fuel | Relevant Parameters* | Reference |
|---|---|---|
| A | Diesel input = 577,776 Btu/dry ton | CA-GREET default |
| B | % Fuel share diesel boiler = 0% | CA-GREET default |
| C | Boiler $CO_2$ emissions = 78,167 g/mmBtu | CA-GREET default |
| D | % Fuel share diesel stationary engine = 20% | CA-GREET default |
| E | IC Engine $CO_2$ Emissions =77,401 g/mmBtu | CA-GREET default |
| F | % Fuel share diesel turbine = 0% | CA-GREET default |
| G | Turbine $CO_2$ emissions 78,179 g/mmBtu | CA-GREET default |
| H | % Fuel share diesel tractor = 80% | CA-GREET default |
| I | Tractor $CO_2$ emissions = 77,204 g/mmBtu | CA-GREET default |
| J | Crude production $CO_2$ emissions = 3,868 g/mmBtu | CA-GREET calculation |
| K | Diesel loss factor = 1.0 | CA-GREET default |
| L | Diesel production $CO_2$ emissions = 9,389 g/mmBtu | CA-GREET default |
| M | Electricity input = 34,924 Btu/ton | CA-GREET default |
| N | Electricity feedstock $CO_2$ emissions = 6,833 g/mmBtu | CA-GREET Calculation |
| O | Electricity fuel $CO_2$ emissions = 213,458 g/mmBtu | CA-GREET calculation |

Note: The calculations for $CH_4$ and $N_2O$ are in similar ways but with different values of emission factors.
*Relevant parameters here are calculated values in CA-GREET, except for technology shares, which are direct inputs.

VOC, CO, $CH_4$, and $N_2O$ emissions are calculated with the same equations, energy input, and loss factors as $CO_2$ emissions calculations shown in Tables 1.05 and 1.06 but with different VOC, CO, $CH_4$, and $N_2O$ emission factors. Table 1.07 shows the results of the calculations of VOC, CO, $CH_4$, and $N_2O$ in (g/dry ton) then converted to g/mmBtu and finally expressed as $gCO_2e$/MJ.

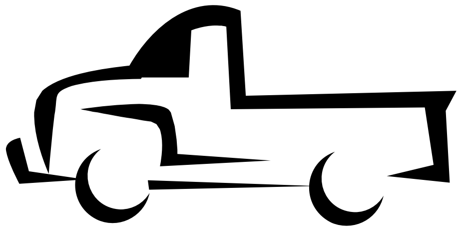
*Table 1.07. GHG Emissions from Forest Waste Collection*

| **Emission Species** | **Emissions[1] (g/dry ton)** | **GHG ($gCO_2e/mmBtu$)** |
|---|---|---|
| VOC | 11.4 | 67.87 |
| CO | 43.19 | 35.48 |
| $CH_4$ | 10.4 | 260 |
| $N_2O$ | 0.1 | 29.8 |
| $CO_2$ | 59,960 | 8,692 |
| Total GHG ($gCO_2e/mmBtu$) | | 9,085 |
| **Total GHG ($gCO_2e/MJ$)** | | **8.6** |

Note: [1]Emissions in grams of gaseous species per dry ton.
To convert all VOC, CO, $CH_4$ and $N_2O$ (g/ton) to (g/mmBtu):
(g/ton)/(Ethanol Yield (gal/ton) * LHV of Anhydrous Ethanol (Btu/gal))*$10^6$

(This page intentionally left blank.)

# SECTION 2. FOREST WASTE TRANSPORT



### 2.1 Energy for Forest Waste Transportation

Transporting forest waste from the removal site to the ethanol plant is accomplished by diesel trucks. Table 2.01 below shows the transportation distance and energy inputs. The calculations are based on heavy duty truck capacities of 15 tons respectively. The default distance transport distance is 75 miles from the source to the ethanol plant. CA-GREET calculates the diesel energy per ton mile based cargo capacity of the truck and its fuel economy and assumes that truck trips carrying forest waste and returning empty use the same energy. All values are CA-GREET default values.

*Table 2.01. Forest Waste Transport Inputs*

| Transport Mode | Energy Intensity (Btu/ton-mile) | Distance from Origin to Destination (mi) | Capacity (tons) | Fuel Cons. (mi/gal) | Energy Cons. of Truck (Btu/mi) | Shares of Diesel Used |
|---|---|---|---|---|---|---|
| Forest to Ethanol Plant by Heavy Duty Truck | 1,511 | 75 | 15 | 5 | 25,690 | 100% |

The calculated transport energy on a Btu per ton and on an anhydrous ethanol basis is shown below in Table 2.02.

*Table 2.02. Forest Waste Transport Energy*

| Transport Mode | Energy Consumption (Btu/ton) | Energy Consumption (Btu/dry ton) |
|---|---|---|
| Forest to Ethanol Plant by Heavy Duty Truck (with assumed 20% waste moisture content) | 263,629 | 263,629 Btu/ton/(1-20%) = 329,536 |
| **Total** | | **47,773 (Btu/mmBtu)** |

Note :
To calculate Energy Consumption :
75 miles *(1511+1511)(Btu/ton-mile)*100%*(1+0.163) = 263,629 Btu/ton

## 2.2 GHG Emissions from Forest Waste Transportation

GHG from forest waste transportation are calculated from section 3.1 above with the same transportation mode, miles traveled, etc. as indicated by Table 2.01 above. Tables 2.03 below detail key assumptions of calculating GHG from forest waste transportation. All values used in calculations are CA-GREET default values.

*Table 2.03. Key Assumptions in Calculating GHG Emissions from Forest Waste Transportation to Ethanol Plant*

| **Transport Mode** | **Energy Intensity (Btu/ton-mile)** | **Distance 1-way (mi)** | **$CO_2$ Emission Factors of Truck (g/mi)** | **$CO_2$ Emission Factors of Diesel used as transportation fuel (g/mmBtu)** |
|---|---|---|---|---|
| Field to Ethanol Plant by Heavy Duty Truck | 1,511 | 75 | 1,999 | 77,809 (77,912 for return trip) |

The calculated forest waste transport energy on g/dry ton of forest waste basis, then converted to g/mmBtu is shown in Table 2.04 below.

*Table 2.04. Forest Waste Transport - $CO_2$ Emissions in g/mmBtu*

| **Transport Mode** | **$CO_2$ Emission (g/ton)** | **$CO_2$ Emission (g/mmBtu)** |
|---|---|---|
| Forest site to Ethanol Plant by Heavy Duty Truck | 25,818 | 3,743 |
| **Total ($gCO_2/MJ$)** | | **3.55** |

Note: Example formula to calculate $CO_2$ emission of Heavy Duty Truck above:

- For origin to destination:

((77,809 g/mmBtu diesel $CO_2$ EF for HDD truck+ 13,257 g/mmBtu diesel $CO_2$ EF)*100% diesel used)*1,511 (Btu/ton-mile) *75 miles/($10^6$ mmBtu/Btu) = 10,333 g/ton

- For the return trip :

((77,912 g/mmBtu diesel $CO_2$ EF for HDD truck+ 13,257 g/mmBtu diesel $CO_2$ EF)*100% diesel used)*1,511 (Btu/ton-mile) *75 miles/($10^6$ mmBtu/Btu) = 10,321 g/ton

- Adjusted to 20% moisture content in the waste and both ways truck travel:

(10,333+10,321)/(1-20%) = 25,818 g/ton

Similarly, $CH_4$, $N_2O$, VOC, and CO are calculated the same way (with different emission factors for each emission) and shown in Table 2.05. Then all emissions are converted to $CO_2$ equivalent based as shown in Table 2.06.

*Table 2.05. Other GHG Emissions of Forest Waste Transport in g/mmBtu*

| Transport Mode | $CH_4$ | $N_2O$ | VOC | CO |
|---|---|---|---|---|
| Forest site to Ethanol Plant by Heavy Duty Truck | 4.1 | 0.09 | 1.53 | 6.83 |

*Table 2.06. Forest Waste Transport – Total GHG Emissions*

| Transport Mode | $CH_4$ ($gCO_2e$/ mmBtu) | $N_2O$ ($gCO_2e$/mmBtu) | VOC and CO Conversion (g/mmBtu) | $CO_2$ (g/mmBtu) | GHG ($gCO_2e$/ mmBtu) | GHG (g/MJ) |
|---|---|---|---|---|---|---|
| Stack to Ethanol Plant Heavy Duty Truck | 4.1*25 = 100.25 | 0.09*298 = 26.8 | **VOC:** 1.53*0.85/ 0.27 = 4.8 **CO:** 4.8*0.43/0.27 = 10.7 | 3,742 | 3,873 | **3.67** |

(This page intentionally left blank.)

# SECTION 3. ETHANOL PRODUCTION

### 3.1 Ethanol Production Energy Use

The fuel pathway analyzed here involves the gasification of forest waste and subsequent conversion to ethanol. A gasifier converts all of the material to a synthesis gas containing CO, $CH_4$ and other gaseous species. A portion of the gas then is converted to ethanol in a bioreactor and the non-reacted gas is converted to process energy.

To calculate the ethanol production, CA-GREET uses energy input values for ethanol from forest waste in Btu/gallon of anhydrous ethanol and uses fuel shares to allocate this direct energy input to process fuels. The fuels used in the ethanol production process are diesel fuel for boilers, engines, and turbines and the energy embedded in the feedstock (forest waste) itself. Table 3.01 below shows the ethanol production diesel shares and energy inputs per gallon of anhydrous ethanol. Co-generation systems can be employed to generate both steam and electricity from lignin of the trees for use on-site. Some amount of extra electricity can be generated in cellulosic plants and be exported to the electric grid. For this pathway in this document, co-generation credit is not considered since the default CA-GREET model scenario does not provide this credit. The average U.S. electric mix is used in the calculations.

*Table 3.01. Primary Energy Inputs (Btu/gallon Ethanol) for Ethanol from Forest Waste*

| | **Fuel Share** | **Primary Energy Input** |
|---|---|---|
| Conventional Diesel | 0.5% | 337 Btu/gal |
| Forest waste combustion | 94.5% | 0.01107 Btu/gal |
| Natural Gas | 5% | 3,236 Btu/gal |

<u>By default, the mass share of feedstock that is used for ethanol is 45%. The remaining energy (55%) goes towards combustion for power and steam generation.</u>

Note: The CA-GREET model has not examined process simulation data for forest waste to ethanol pathway but the assumption used here is that this ratio should be lower than that for herbaceous biomass to ethanol pathway because of high lignin content of forest waste.

CA-GREET uses the direct, primary energy inputs for ethanol production to calculate the total energy required to deliver each primary energy input. Tables 3.02 and 3.03 below show the CA-GREET equations, parameters and energy inputs for ethanol production. The tables show the total input energy per mmBtu of anhydrous ethanol.

*Table 3.02. Forest Waste Ethanol Production Formulas, Parameters, and Total Energy*

| Fuel Type | Formula | Relevant Parameters | Total Energy (Btu/gal) |
|---|---|---|---|
| Diesel | CA-GREET Default | Direct diesel energy used in process | 337 |
| | Direct diesel energy *((Crude*Loss Factor) / $10^6$ = (337Btu/gal * 39,212 Btu/mmBtu*1)/$10^6$ | Energy upstream from crude (see Table 1.04) | 13.2 |
| | Direct diesel energy * WWT of diesel = (337 Btu/gal * 123,805 Btu/mmBtu*1)/$10^6$ | Energy WTT of diesel (see Table 1.04) | 41.7 |
| **Total energy contribution from diesel** | | | 392 |
| Forest Waste | (1/90.4 tons/gal)*(LHV of waste 13,243,490 Btu/ton) | 45% of forest waste used as fuel: for 1 gallon of ethanol, 1/90.4 or 0.01107 tons of waste needed | 146,547 |
| | | Ethanol energy extracted from forest waste | (-76,330) |
| **Total energy contribution from forest waste** | | | 70,217 |
| NG | Direct NG energy * (1+WTT upstream of NG) = 3236*(1+69,596/$10^6$) | Direct NG energy and energy upstream of NG | 3,461 |
| **Total energy contribution from NG** | | | 3,461 |
| Loss | | Loss Factor in the process | 1.0005 |
| Total energy input for forest waste ethanol production (Btu/gal) | | | 74,071 |
| **Total energy input (Converted to Btu/mmBtu)** | | **(74,071 Btu/gal/76,330 Btu/gal)*1.0005 *$10^6$** | **970,889** |

### 3.2 GHG Emissions from Ethanol Production

GHG from ethanol production is calculated based on the assumptions in Table 3.03 below and the results are shown in Table 3.04. As indicated in the previous section, the majority of direct energy used is from waste burning (94.5%), plus a small amount of diesel and natural gas (5%) used in the process. These shares of energy are multiplied with the GHG emission factors of equipments used.

*Table 3.03. Process Shares and Emission Factors (EF) of Ethanol Production Equipment by CA-GREET Default*

| EtOH Production Equipment and Fuel Used | % Shares of Equip. Usage | $CO_2$ EF (g/mmBtu of fuel burned) | VOC EF | CO EF | $CH_4$ EF | $N_2O$ EF | Assumed % of Fuels used |
|---|---|---|---|---|---|---|---|
| large industrial boiler | 33% | 78,167 | 1.17 | 16.69 | 0.18 | 0.19 | 0.1% |
| stationary engine | 33% | 77,401 | 70.44 | 361 | 3.9 | 2 | |
| diesel turbine | 34% | 78,179 | 1.33 | 8.71 | 0.84 | 2 | |
| natural gas boiler | 100% | | | | | | |
| forest waste gasifier | 100% | 129,823 | 5.34 | 76.8 | 3.83 | 11 | 99.9% |

*Table 3.04. Calculated $CO_2$ Emissions (g/gal) for Forest Waste Ethanol Production Using $CO_2$ Factors from Table 3.03*

| | Calculations $CO_2$ in g/gal | | Conversion to $CO_2$ (g/mmBtu) | Results |
|---|---|---|---|---|
| **From Diesel combustion** | | | | |
| large industrial boiler | $337*33\%*78,167/10^6 = 8.7$ | 26.3 | (26.3 g/gal)/(76,330 Btu/gal)*$10^6$ | 344.6 |
| stationary engine | $337*33\%*77,401/10^6 = 8.6$ | | | |
| diesel turbine | $337*34\%*78,179/10^6 = 9$ | | | |
| WTT diesel | $337*(2,899*1+8,987)/10^6 = 4$ (see table 1.06 for diesel WTT) | 4 | (4 g/gal)/(76,330 Btu/gal)*$10^6$ | 52.4 |
| **From Waste Energy** | | | | |
| forest waste gasifier | $0.01107*(1-45\%)*(129,823/10^6)*13,243,490$ | 10,464 | (10,464 g/gal)/(76,330Btu/gal) *$10^6$ | 137,136 |
| **Natural Gas** | | | | |
| large industrial boiler | $3,236*58,198/10^6$ | 205 | (205 g/gal)/(76,330 Btu/gal) *$10^6$ | 2,688 |
| Loss factor | | | | 1.001 |
| **Total GHGs ($gCO_2$/mmBtu) = (344.6 + 52.4 + 137,136 + 2,688) *1.001** | | | | **140,248** |

Note: Feed Loss Factor is assumed at 1.001

Similar calculations for VOC, CO, $CH_4$, and $N_2O$ are calculated and the total for all species are as shown in the Table 3.05 below. Therefore, the total GHG (in $CO_2$e/MJ) for ethanol from forest waste is **136.6** $CO_2$e/MJ (anhydrous).

*Table 3.05. GHG Emissions for Ethanol Production*

| GHG Species | GHG Emissions g/gal | GHG Emissions g/mmBtu |
|---|---|---|
| VOC | 0.47 | 6.2 |
| CO | 6.3 | 82.5 |
| $CH_4$ | 0.76 | 10.0 |
| $N_2O$ | 0.89 | 11.7 |
| $CO_2$ | 10,700 | 140,248 |
| Total GHGs (g$CO_2$e/mmBtu) | 10,984 | 144,101 |
| **Total GHGs (g$CO_2$e/MJ)** | | **136.6** |

Table 3.06 shows the GHG credit from burning wastes that is used in the ethanol plant. The amount of $CO_2$ that is from burnt trees is considered carbon neutral since it was from $CO_2$ in the atmosphere fixed by the feedstock during its growth. Thus the net GHG emissions emitted to the atmosphere are **136.6-130.1 = 6.5 g/MJ** of ethanol from the production facility.

*Table 3.06. GHG Emission Credits from Burning Forest Waste as Fuel in Ethanol Plant*

| **Emissions** | |
|---|---|
| $CO_2$ (g/gal) | -10,476 |
| $CO_2$ (g$CO_2$e/mmBtu) | -137,312 |
| **GHG (g$CO_2$e/MJ)** | **-130.15** |

Note: trees burning credit is calculated as following:
(1/(90.4 gal/dry ton)) *(1-45%)*51.7% C ratio*(2000 lb/dry ton)*(454 g/lb)*(44 of $CO_{2)}$/(12 of C))*loss factor = (1/(90.4) * (1-45%) * 55% * 2000 * 454 *(44/12) * 1.0005 = 137,312
Where:

- ethanol from forest waste yield: 90.4 gal/dry ton
- 45% is the mass of forest waste to make ethanol
- (1-45%) is the mass of forest waste to make power and steam in the process
- loss factor is 1.0005

(This page intentionally left blank.)

# SECTION 4. ETHANOL TRANSPORT AND DISTRIBUTION

### 4.1 Energy for Ethanol Transportation and Distribution

Transport from the ethanol plant to the bulk terminal or storage facility is accomplished primarily by rail (with short truck delivery to terminal or storage facility). The transport distance based on AB1007 analysis is 1,400 miles by rail and 40 miles by truck. The local distribution step involves transporting ethanol to a gasoline blending terminal where it is blended with gasoline to produce CaRFG. Ethanol is transported by truck to the blending terminal. The CaRFG is then transported to the local fueling station. The estimated distribution distance is 50 miles based on the AB1007 analysis.

Instead of calculating the WTT values on a per ton basis as CA-GREET does for the Forest waste transport component, CA-GREET calculates WTT energy required per mmBtu of fuel (anhydrous ethanol) transported. Table 4.01 below shows the major inputs used in calculating transport energy and Table 4.02 presents the CA-GREET equations used to calculate the ethanol transport energy for each transport mode.

*Table 4.01. Inputs and Calculated Fuel Cycle Energy Requirements for Ethanol Transport to Bulk Terminals*

| Transport | Mode | Energy Intensity (Btu/ton-mile) | Distance from Origin to Destination (mi) | Capacity (tons) | Fuel Used (mi/gal) | Energy Used of Truck (Btu/mi) | Shares of Diesel Used | % Fuel Transported by Mode |
|---|---|---|---|---|---|---|---|---|
| Plant to Bulk Terminal | Heavy Duty Truck | 1,028 | 40 | 25 | 5.0 | 25,690 | 100% | 70% |
| | Rail | 370 | 1,400 | n/a | n/a | n/a | 100% | 100% |
| Distribution | Heavy Duty Truck | 1,028 | 50 | 25 | 5.0 | 25,690 | 100% | 100% |

*Table 4.02. CA-GREET Calculations for Ethanol Transport Energy (Btu/mmBtu Ethanol) by Transport Mode*

| Transport Mode | CA-GREET Formula | Relevant Parameters | Btu/mmBtu |
|---|---|---|---|
| **Transport**<br><br>Heavy Duty Truck | $(10^6/(76330))*(2988)/((g/lb)*(lb/ton)*(40)*2*(1028)*((100\%)*(1+0.163))$ | Ethanol LHV = 76,330 Btu/gal<br>Ethanol density = 2,988 g/gal<br>Miles traveled = 40<br>Energy intensity = 2*(1,028 Btu/ton-mile)<br>%Diesel Share = 100%<br>Diesel energy = 0.163 Btu/Btu | 4,122 |
| **Transport**<br><br>Rail | $10^6/(76330)*(2988)/((g/lb)*(lb/ton)*(1400)*(370)*((100\%)*(1+2.647))$ | Miles traveled = 1,400<br>% Electricity share = 0%<br>Electric rail energy intensity = 370 Btu/ton-mile<br>Electricity Energy = 2.647 Btu/Btu | 25,973 |
| **Transport**<br><br>**Total** | (70%)(4,122 Btu/mmBtu) +(100%)(25,973 Btu/mmBtu) | Fuel transported by truck = 70%<br>% Fuel transported by rail 100% | **28,858** |
| **Distribution** | $(100\%)*(10^6)/(76330)*(2988)/((g/lb)*(lb/ton)*(50)*(2*1028)*(100\%)$ | Miles traveled = 50 | 5,152 |
| **T&D Total (Btu/mmBtu)** | | | **34,010** |

Note that the energy intensity for heavy duty trucks is multiplied by 2 to account for return trip.

## 4.2 GHG Calculations from Ethanol Transportation and Distribution

Similar to forest waste T&D, ethanol T&D to bulk terminal is assumed in CA-GREET model by rail carts and then to destination by truck. All the key assumptions are the same as forest waste T&D's and are shown in Table 4.03.

*Table 4.03. Key Assumptions in Calculating GHG Emissions from EtOH Transportation*

| Transport Mode | 1-way Energy Intensity (Btu/ton-mile) | Distance from Origin to Destination (mi) | $CO_2$ Emission Factors (g/mi) | $CO_2$ Emission Factors of Diesel used as transportation fuel (g/mmBtu) | $CO_2$ Emission Factors of Diesel Combustion (g/mmBtu) |
|---|---|---|---|---|---|
| 100% Rail | 370 | 1,400 | | 13,257 | 77,664 |
| 100% transport and 70% distribution by Heavy Duty Truck | 1,713 | 40 | 1,999 | 13,257 | 77,798 |

Note: Assumed all locomotives use diesel

The results are shown below in Table 4.04. The WTT emissions shown in the Table for each GHG species is calculated in the *T&D* tab of CA-GREET. The equation for $CO_2$ from rail is shown below and the calculations for the other transport modes and GHG gases are done similarly. Note that only one-way rail emissions are counted, whereas an extra term exists in the calculation for truck transport to account for the return truck trip; emissions from the return trip are assumed to be equal to emissions for the trip from the origin to destination.

**Rail $CO_2$ emissions** = (Ethanol density 2,988 g/gal)/(Ethanol LHV 76,330 Btu/gal)/[(454 g/lb)*(2,000 lbs/ton)]*[(Diesel emission factor 77,664 g/Btu)+(Diesel WTT emissions 13,257 g/mmBtu)]*(370 Btu/ton-mile)*(1400 miles) = 2,030 g/mmBtu ethanol.

*Table 4.04. EtOH Transport - $CO_2e$ Emissions in g/mmBtu*

| **Transport Mode** | **$CO_2$ Emission (g/mmBtu)** | **$CH_4$ to $CO_2e$ (g/mmBtu)** | | **$N_2O$ to $CO_2e$ (g/mmBtu)** | | **VOC* to $CO_2e$ (g/mmBtu)** | **$CO_2e$ (g/mmBtu)** |
|---|---|---|---|---|---|---|---|
| Transported by Rail | 2,030 | 2.28 | 53.7 | 0.05 | 14.2 | | 2,102 |
| Transported by Heavy Duty Truck | 226 | 0.25 | | 0.01 | | | 234 |
| Distributed by Heavy Duty Truck | 404 | 0.44 | 10.4 | 0.01 | 3 | 19.75 | 480 |
| Total | 2,660 | | 70 | | 16 | | 2,815 |
| **Total ($gCO_2e/MJ$)** | | | | | | | **2.67** |

Note: VOC from non-combustion leakage sources

(This page intentionally left blank.)

# SECTION 5. COMBUSTION EMISSIONS FROM FUEL

## 5.1 Combustion Emissions

Ethanol is assumed to not be used directly as a fuel in California. It is also blended with a denaturant before it is transported. This document provided details for anhydrous ethanol. Details of denaturant blending and use of this blend in CARBOB to produce CaRFG is detailed in the CaRFG document available on the LCFS website. When used in CaRFG, $CO_2$ emissions from ethanol are considered to be ‘zero’ since $CO_2$ was ‘fixed’ from the atmosphere by the forest waste (biomass) during its growth.

(This page intentionally left blank.)

# APPENDIX B

## ETHANOL PATHWAY INPUT VALUES (FROM MIDWEST FOREST WASTE)

## Ethanol made in Midwest from Midwest Forest waste and transported to California

| Parameters | Units | Values | Note |
|---|---|---|---|
| **GHG Equivalent** | | | |
| $CO_2$ | | 1 | |
| $CH_4$ | | 25 | |
| $N_2O$ | | 298 | |
| VOC | | 3.1 | |
| CO | | 1.6 | |
| **Forest Waste Collection** | | | |
| **Fuel Use Shares** | | | |
| *Diesel* | | 94.3% | |
| *Electricity* | | 5.7% | |
| **Collection Equipment Shares** | | | |
| *Diesel Farming Tractor* | | 80% | |
| *$CO_2$ Emission Factor* | g/mmBtu | 77,204 | |
| *Diesel Engine* | | 20% | |
| *$CO_2$ Emission Factor* | g/mmBtu | 77,349 | |
| *Forest waste collection energy use* | Btu/dry ton | 612,700 | |
| **Forest Waste Collection T&D** | | | |
| *Transported from Forest to EtOH Plant* | | | |
| *by heavy duty diesel truck* | miles | 40 | 1,713 Btu/mile-ton Energy Intensity |
| *fuel consumption* | mi/gal | 5 | capacity 15 tons/trip |
| *$CO_2$ emission factor* | g/mi | 1,999 | |
| ***EtOH T&D*** | | | |
| *Transported by rail* | miles | 1,400 | 370 Btu/mile-ton Energy Intensity |
| *Transported by HHD truck* | miles | 40 | 1,028 Btu/mile-ton Energy Intensity both ways |
| *Distributed by HHD truck* | miles | 50 | 1,028 Btu/mile-ton Energy Intensity both ways |
| **Fuels Properties** | **LHV (Btu/gal)** | **Density (g/gal)** | |
| *Crude* | 129,670 | 3,205 | |
| *Residual Oil* | 140,353 | 3,752 | |
| *Conventional Diesel* | 128,450 | 3,167 | |
| *Conventional Gasoline* | 116,090 | 2,819 | |
| *CaRFG* | 111,289 | 2,828 | |
| *CARBOB* | 113,300 | 2,767 | |
| *Natural Gas* | 83,868 | 2,651 | As liquid |
| *EtOH* | 76,330 | 2,988 | Anhydrous ethanol |
| *EtOH* | 77,254 | 2,983 | Denatured ethanol |
| *Forest Waste* | 13,243,490 | | In Btu/ton |

[1] GREET Model: Argonne National Laboratories:
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
[2] California Assembly Bill AB 1007 Study: http://www.energy.ca.gov/ab1007
[3] CA_GREET Model (modified by Lifecycle Associates ) released February 2009 (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm)
[4] USDA – Forest Inventory and Analysis – "Forest Resources of the United States, 2002"– Table 41 - www.fia.fs.fed.us/documents/pdfs/2002_RPA FINAL TABLES.pdf
[5] Forest Encyclopedia (http://www.forestryencyclopedia.net/p/p1247/view) - p.1247
[6] Intergovernmental Panel on Climate Change is a scientific intergovernmental body tasked to evaluate the risk of climate change caused by human activity established by United Nations in 1988. "*IPCC Technical Report 2007*" – Table TS-2 – page 33 (http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-ts.pdf).